Nucleosynthesis in Early Neutrino Driven Winds

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Abstract. Two recent issues realted to nucleosynthesis in early proton-rich neutrino winds are investigated. In the first part we investigate the effect of nuclear physics uncertainties on the synthesis of ^{92}Mo and ^{94}Mo. Based on recent experimental results, we find that the proton rich winds of the model investigated here can not be the only source of the solar abundance of ^{92}Mo and ^{94}Mo. In the second part we investigate the nucleosynthesis from neutron rich bubbles and show that they do not contribute to the nucleosynthesis integrated over both neutron and proton-rich bubbles and proton-rich winds.

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INTRODUCTION

Over the past decade improvements in neutrino-transport and multi-dimensional computer simulations have lead to a new understanding of the conditions that lead to nucleosynthesis of the elements above iron in core-collapse supernovae. Immediately following the bounce on the proto-neutron star, the shock fully photodisintegrates the infalling material turning it into electron–position pairs, neutrons, and protons. As the nascent neutron star continues to collapse it liberates 10^{53}ergs over the span of ~ 10 seconds primarily in the form of neutrinos. This enormous neutrino flux is deposited in the low density region of photodisintegrated matter inside the gain radius between the neutron star and the accretion shock of the still infalling material and heats it to temperatures in excess of 10 billion K while driving mass away in the form of a neutrino wind theoretically leading to the explosion of the supernova [1]. The strong flux of neutrinos and anti-neutrinos results in a detailed balance between protons and neutrons that favors the lighter mass protons depending on the respective neutrino spectra leading to an electron fraction that is proton-rich ($Y_e > 0.5$) [2, 3]. These protons and neutrons recombine into alpha particles that proceed via the $\alpha(\alpha n,\gamma)$ ^{9}Be(α,n) ^{12}C-reactions followed by a series of (α,γ)-reactions or combined $(\alpha,p)(p,\gamma)$-reactions along $N = Z$ into the iron group, primarily ^{56}Ni and ^{60}Zn which form the seeds of the subsequent nucleosynthesis.

From this point the resulting nucleosynthesis in the neutrino-driven wind essentially depends on the number of seed nuclei to the number of excess neutrons or protons that were frozen out and did not turn into seed nucleii (Y_e), the entropy per baryon, the expansion timescale of the ejecta and the amount of the ejecta. As the explosion evolves, an ejected mass element inherits some combination of these parameters and below ~ 0.5MeV they remain fairly constant as the matter proceeds to freeze out.

In this paper, we consider the early times when the wind still contains a proton excess because the rates for neutrino and positron captures on neutrons are faster than those for the inverse captures on protons. We consider two interesting problems which are discussed in the following two sections.

THE PUZZLE OF ^{92}Mo

The origin of ^{92}Mo is a long standing puzzle of nucleosynthesis [for reviews, see 4, 5]. It is thought to originate in the proton-rich wind prior to the r-process in core collapse supernovae, but historically it has been underproduced in such models or subject to severe model constraints [6, 7].

Recent supernova models show that the $Y_e \equiv \sum X_i Z_i/A_i$ of the innermost ejecta is greater that the Y_e of the most abundant p-nuclei [1, 3]. This implies the existence of surplus protons which allow the production of proton-rich p-nuclei nuclei by the νrp-process [8]. However, similar to the rp-process in the X-ray burst scenario, there is an important waiting point at ^{64}Ge which backs up material beyond the $t < 1$s dynamic timescale of the innermost ejecta in core collapse [9].

To solve this problem, it was suggested a new νp-process in which neutrinos convert some of the surplus protons into neutrons allowing the waiting points to be bridged via an (n,p)-reaction [10]. This accelerates the flow into heavier elements and creates the light p-nuclei which are otherwise missing from the standard r-process.

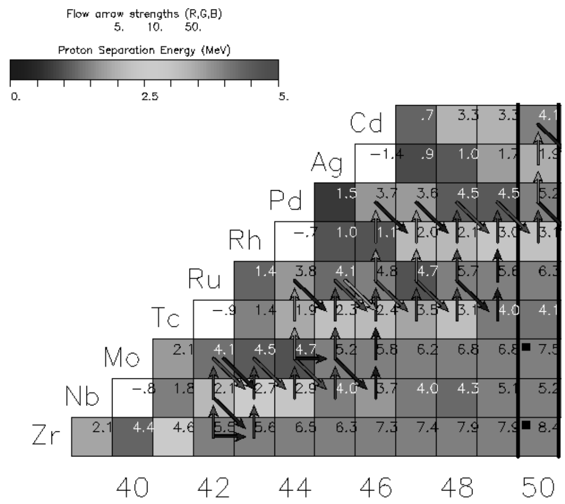

FIGURE 1. A closeup of Figure 8 in [8] for the region between Zr and Cd when $T_9 = 2.06, \rho_5 = 2.74,$ and $Y_e = 0.561$ showng nuclear flows in the $A \sim 90$ region. Each isotope is labled according to its proton separation energy The arrows indicate the dominant net nuclear flows. All net flows within a factor of 50 of the largest flow in this figure (^{84}Nb$(p,\gamma)^{85}$Tc $= 4.5 \times 10^{-5}$s^{-1}) are shown. The most important flows affecting ^{92,94}Mo are the proton capture flows on ^{92}Ru and ^{93}Rh.

These calculations were independently confirmed by calculations based on simulations [8, 11].

Still, relative to the solar abundances, both calculations show underproduction of ^{92}Mo (the most abundant of the *p*-nuclei) relative to the *p*-nuclei of Ru and Pd. There are three possible reasons why ^{92}Mo is not co-produced with the other *p*-nuclei: 1) The νp-process is active, but ^{92}Mo is primarily synthesized at other sites. 2) The νp-process is not active, so another explanation is needed. 3) The νp-process is active, but the nuclear parameters that enter the nucleosynthesis calculation are incorrect. In this paper, we investigate the third possibility.

The production of the light *p*-nuceli

Nucleosynthesis results obtain from the sum total of the reaction flow in all the matter trajectories of the supernova ejecta. Here we only consider the reaction flow in "trajectory 6" (see Table 2 of [8]) based on the model of [11] (see [12] for specific code details and [13] for more details). "Trajectory 6" is the trajectory where neutrino interactions are the most important in making the *p*-nuclei between Sr and Pd.

The νp-process starts on the iron group but it is halted at the long-lived ^{64}Ge waiting point which is known to be bridged by an (n,p)-reaction allowing the νp-process to continue [10]. The flow from ^{64}Ge passes through all even-even $T_z = (N-Z)/2 = 0$ isotopes until ^{88}Ru is reached [8]. As fig. 1 shows, the pattern is broken because of the low proton separation energy of ^{90}Ru that prevents immediate proton captures up to ^{92}Pd. Instead the flow proceeds via ^{90}Ru(n,p) ^{90}Tc(p,γ) ^{91}Ru. A (p,γ)-reaction would result in the ^{92}Rh progenitor provided it does not get destroyed by another (p,γ)-reaction. Alternatively, an (n,p)-reaction to ^{91}Tc followed by a (p,γ)-reaction would result in the ^{92}Ru progenitor once again provided it does not get destroyed by another (p,γ)-reaction. In both cases the reverse reactions from ^{93}Pd and ^{93}Rh would increase the survival of the $A = 92$ progenitors.

Many of the relevant reaction rates, spins, partition functions, and proton separation are not known experimentally and the theoretical values are subject to considerable uncertainties which may change the flow. For instance, a 50% yield increase in ^{92}Mo was found after a plausible 1 MeV increase in the proton separation energy of ^{91}Ru [13].

We systematically investigated the effect relevant nuclear uncertainties on this reaction flow using the model described in [8, 13]. We find that variation within current uncertainties [14] of the ^{91}Rh proton separation energy and the ^{92}Rh proton separation energy does not change the solar abundance ratio of ^{92}Mo to^{94}Mo whereas the ratio is highly sensitive to the proton separation energy of ^{93}Rh. Fig. 2 shows the dependence of the solar ratio ^{92}Mo to ^{94}Mo to variations in entropy of "trajectory 6". We show that $S_p(^{93}\mathrm{Rh}) = 1.63$ MeV is a solution to a range of entropy variations between 0.8 and 1.6 of the nominal value. The figure also shows no solution above $S_p(^{93}\mathrm{Rh}) = 1.71$ MeV.

Fig. 3 shows the dependence of the solar ratio ^{92}Mo to^{94}Mo to variations in entropy in "trajectory 6" as a function of Y_e and $S_p(^{93}\mathrm{Rh})$. The figure also shows the solutions where ^{92}Mo and ^{94}Mo are co-produced within a factor 4,5 and 7. Isotopes produced with precisely the solar abundance pattern have equal production factors. A co-production factor of no more than 7 is typically regarded as acceptable as the global characteristics of nucleosynthesis are sensitive to details of the outflow.

The conclusion that the ^{92}Mo and ^{94}Mo ratio is predominantly influenced by $S_p(^{93}\mathrm{Rh})$ has been shown to be robust (Fisker et al., submitted for publication). However, our calculations predict that $S_p(^{93}\mathrm{Rh}) = 1.63$ MeV whereas recent experimental results suggest that $S_p(^{93}\mathrm{Rh}) = 2.0001 \pm 0.008$ MeV [15]. This leads to the tentative conclusion that proton rich winds under the conditions in the model investigated here can not be the sole source of the solar ^{92}Mo and ^{94}Mo.

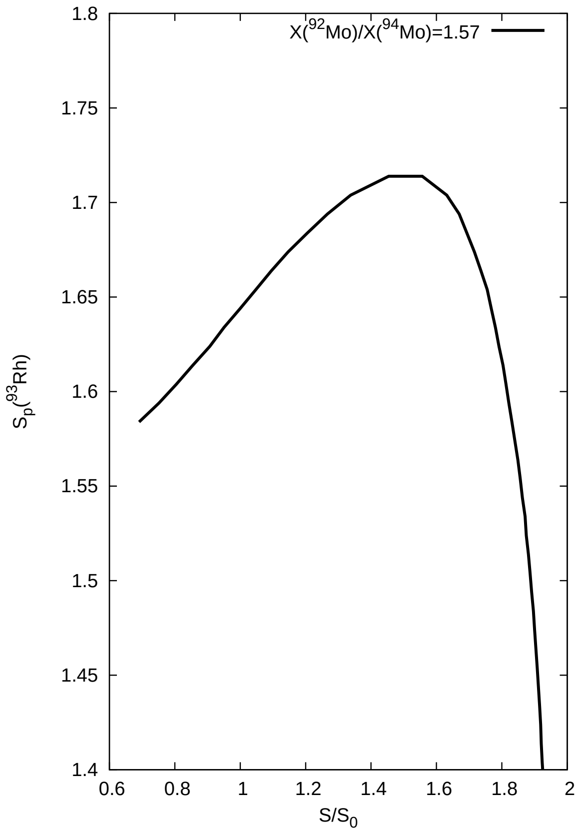

FIGURE 2. The allowed values of $S_P(^{93}\mathrm{Rh})$ as a function of changes in entropy, S relative to the entropy of "trajectory 6", $S_0 = 77$, in the outflowing wind for the solar ratio of $^{92}\mathrm{Mo}/^{94}\mathrm{Mo}$.

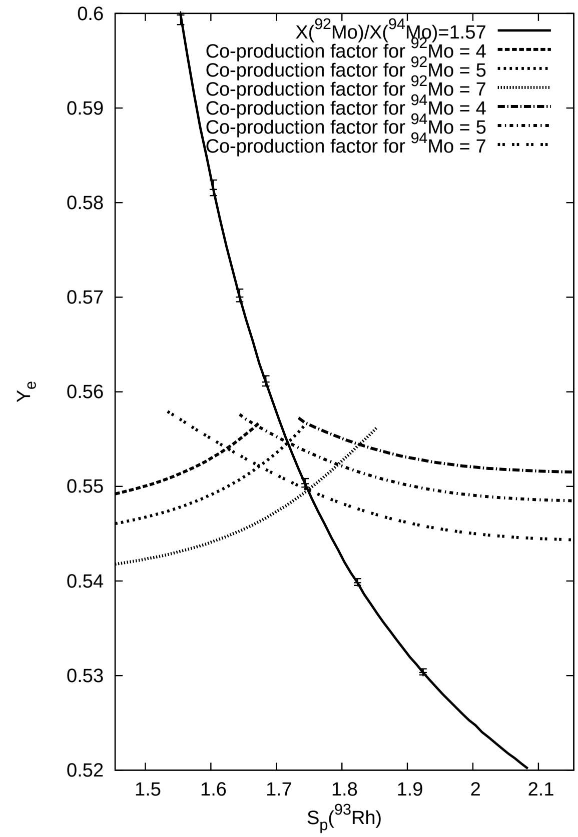

FIGURE 3. The solid line shows the solution for Y_e and $S_P(^{93}\mathrm{Rh})$ where the $^{92}\mathrm{Mo}/^{94}\mathrm{Mo}$ ratio in the outgoing wind matches the solar ratio. Error bars indicate the extent of similar lines for ratios of 1.54 and 1.59. Also shown are the solutions where ^{92}Mo and ^{94}Mo are coproduced within a factor 4, 5, and 7. A solution is found for a co-production factor of 5 with Y_e=0.555 and $S_P(^{93}\mathrm{Rh})$ = 1.72 (see main text for details).

THE CONTRIBUTION FROM NEUTRON RICH POCKETS

Using the same supernova model as above, the contribution to core-collapse nucleosyntheis of the proton-rich bubbles and proton-rich winds was investigated in [13, 8] However, some bubbles also contains neutron-rich matter that is ejected in coincidence with the proton-rich bubbles. Here, investigate their contribution to the overall nucleosynthesis by considering newly extrated trajectories with $0.47 \leq Y_e \leq 0.50$.

For Y_e closer to 0.5, primarily ^{56,57,58}Ni are formed. The flow from these nuclei leads to ^{64}Ge. Unlike the νp-process [10], there is not a sufficient amount of protons left at this time for neutrinos provide sufficient numbers of neutrons to capture on ^{64}Ge and thus move beyond this waiting point. As a result, heavier isotopes are not co-produced with the ^{62}Ni and ^{64}Zn isotopes. In particular, there is no overproduction of the light p-nuclei for $Y_e \leq 0.5$. For Y_e closer to 0.47, primarily ^{58,59,60}Ni are formed. This means that the ^{64}Ge waiting point is circumvented which leads to overproduction of ^{74}Se, ^{78}Kr, and ^{92}Mo which is co-produced with ^{64}Zn. With decreasing Y_e, ^{92}Mo production falls off and the overproduction of N=50 nuclei ensues.

The figure shows the integrated production factors for all studied neutron-rich bubble trajectories. The most produced isotopes in the neutron-rich parts of the bubble relative to solar abundances are ^{62}Ni and ^{64}Zn which originate in bubbles with Ye closer to 0.5. These are co-produced along with ^{74}Se and ^{78}Kr which originate in the bubbles with Ye closer to 0.47. The neutron-rich bubbles add ^{74}Se, ^{78}Kr, and ^{92}Mo to the bubble-outflow, but this contribution is much smaller than the contribution from the proton-rich winds when neutrino interactions are included. The neutron-rich bubbles also add ^{62}Ni and ^{64}Zn to the total outflow but only in comparable amounts to the wind outflows and the proton-rich bubble outflows.

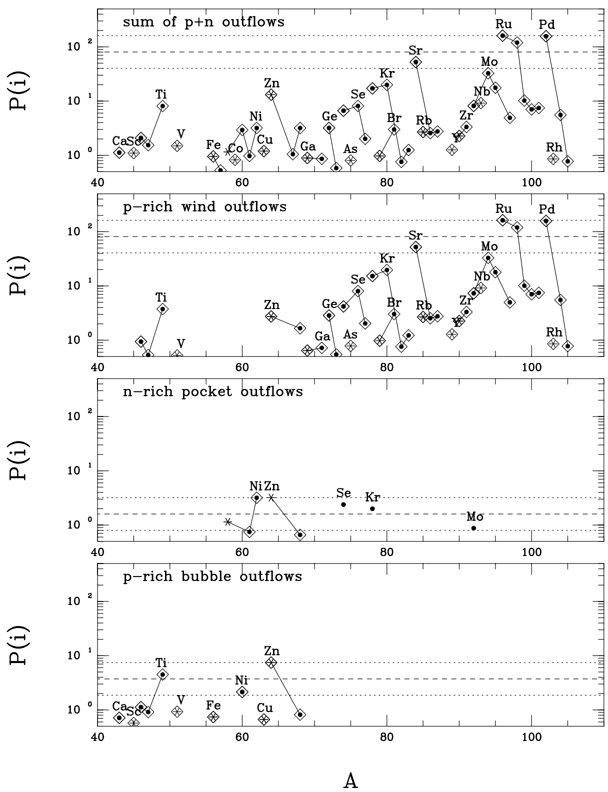

FIGURE 4. Production factors of the neutron-rich trajectories of the convective bubble ejecta. The most abundant isotope for a given element is shown with an asterisk. Diamonds indicate that the isotope was made primarily as a radioactive progenitor.

Our results show that the overproduction factors of the neutron-rich bubbles folded with the mass-ejecta does not contribute significantly to the nucleosynthesis of the light p-nuceli compared to the nucleosynthesis of the proton-rich material.

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REFERENCES

1. Y.-Z. Qian, and S. E. Woosley, *Astrophys. J.* **471**, 331–351 (1996).
2. M. Liebendörfer, A. Mezzacappa, O. E. B. Messer, G. Martínez-Pinedo, W. R. Hix, and F.-K. Thielemann, *Nucl. Phys.* **A719**, 144 (2003).
3. C. Fröhlich, P. Hauser, M. Liebendörfer, G. Martínez-Pinedo, F.-K. Thielemann, E. Bravo, N. T. Zinner, W. R. Hix, K. Langanke, A. Mezzacappa, and K. Nomoto, *Astrophys. J.* **637**, 415–426 (2006).
4. D. L. Lambert, *Astron. Astrophys. Rev.* **3**, 201–256 (1992).
5. B. S. Meyer, *Ann. Rev. Astron. Astrophys.* **32**, 153–190 (1994).
6. G. M. Fuller, and B. S. Meyer, *Astrophys. J.* **453**, 792–809 (1995).
7. R. D. Hoffman, S. E. Woosley, G. M. Muller, and B. S. Meyer, *Astrophys. J.* **460**, 478–488 (1996).
8. J. Pruet, R. D. Hoffman, S. E. Woosley, H.-T. Janka, and R. Buras, *Astrophys. J.* **644**, 1028–1039 (2006).
9. R. K. Wallace, and S. E. Woosley, *Astrophys. J. Suppl.* **45**, 389–420 (1981).
10. C. Fröhlich, G. Martínez-Pinedo, M. Liebendörfer, F.-K. Thielemann, E. Bravo, W. R. Hix, K. Langanke, and N. T. Zinner, *Phys. Rev. Lett.* **96**, 142502 (2006).
11. H.-T. Janka, R. Buras, and M. Rampp, *Nucl. Phys.* **A718**, 269–276 (2003).
12. M. Rampp, and H.-T. Janka, *Astron. Astrophys.* **396**, 361–392 (2002).
13. J. Pruet, S. E. Woosley, R. Buras, H.-T. Janka, R. Buras, and R. D. Hoffman, *Astrophys. J.* **623**, 325–336 (2005).
14. G. Audi, A. H. Wapstra, and C. Thibault, *Nucl. Phys.* **729**, 337–676 (2003).
15. V. Elomaa, R. Ferrer, C. Weber et al., in preparation.